

UNIVERSITY OF CALIFORNIA, SAN DIEGO

NASA-CR-196367

FINAL REPORT

for

Grant NA65-1977

"Search for the X-ray Counterpart of the 5 March 1979

Gamma Ray Burst"

We have analyzed a deep HRI image to find out whether an enhancement in the x-ray flux existed at the site of the gamma ray burst error box, which could be the first identification of a persistent gamma ray burst counterpart. We found such an enhancement and the results were published in Nature (Vol. 368, pages 432-434, 31 March 1994). A copy of the paper is attached.

(NASA-CR-196367) SEARCH FOR THE
X-RAY COUNTERPART OF THE 5 MARCH
1979 GAMMA RAY BURST Final Report
(California Univ.) 4 p

N95-70235

Unclass

Z9/93 0019569

ORIGINAL PAGE IS
OF POOR QUALITY

15. Yun, C. H., Crofts, A. R. & Gennis, R. B. *Biochemistry* **30**, 6747–6754 (1991).
16. Moore G. *FEBS Lett.* **161**, 171–175 (1983).
17. Cramer, W. A., Black, M. T., Widger, W. R. & Girvin, M. E. *Structure and Function of Photosynthetic Cytochrome bc₁ and b₆f Complexes* (Elsevier, Amsterdam, 1987).
18. Davies, A. M. et al. *Biochemistry* **32**, 5431–5435 (1993).
19. DeGrado, W. F., Wasserman, Z. R. & Lear, J. D. *Science* **243**, 622–628 (1989).
20. DeGrado, W. F., Raleigh, D. P. & Handel, T. *Curr. Opin. struct. Biol.* **1**, 984–993 (1991).
21. Howell, N. & Robertson, D. E. *Biochemistry* **32**, 1310–1317 (1993).
22. Alegria, G. & Dutton, P. L. *Biochim. biophys. Acta* **1057**, 239–257 (1991).
23. Alegria, G. & Dutton, P. L. *Biochim. biophys. Acta* **1057**, 258–272 (1991).
24. Palmer, G. *Biochem. Soc. Trans.* **13**, 548–560 (1985).
25. Salerno, J. C. *J. biol. Chem.* **259**, 2331–2336 (1984).
26. Walker, F. A., Huynh, B. H., Scheidt, W. R. & Osvath, S. R. *J. Am. chem. Soc.* **108**, 5288–5297 (1986).
27. Dutton, P. L. *Meth. Enzym.* **54**, 411–435 (1978).
28. Leitch, F. A., Brown, K. R. & Pettigrew, G. W. *Biochim. biophys. Acta* **808**, 213–218 (1985).
29. Harbury, H. A. et al. *Proc. natn. Acad. Sci. U.S.A.* **84**, 1658–1664 (1987).
30. Churg, A. K. & Warshel, A. *Biochemistry* **25**, 1675–1681 (1986).
31. Gunner, M. R. & Honig, B. *Proc. natn. Acad. Sci. U.S.A.* **88**, 9151–9155 (1991).
32. Nicholls, P. & Petersen, L. C. *Biochim. biophys. Acta* **387**, 462–467 (1974).
33. Wikstrom, M. K. F., Harmon, H. J., Ingledew, W. J. & Chance, B. *FEBS Lett.* **65**, 259–277 (1976).
34. Moura, J. J. G. et al. *Eur. J. Biochem.* **127**, 151–155 (1982).
35. Santos, H., Moura, J. J. G., Moura, I., LeGall, J. & Xavier, A. V. *Eur. J. Biochem.* **141**, 283–296 (1984).
36. Fan, K., Akutsu, H., Kyogoku, Y. & Niki, K. *Biochemistry* **29**, 2257–2263 (1990).
37. Moser, C. C., Keske, J. M., Warncke, K., Farid, R. S. & Dutton, P. L. *Nature* **355**, 796–802 (1992).
38. Pace, C. N., Shirley, B. A. & Thompson, J. A. in *Protein Structure: A Practical Approach* (ed. Creighton, T. E.) 311–330 (IRL, Oxford, 1989).
39. Dutton, P. L. & Jackson, J. B. *Eur. J. Biochem.* **30**, 495–510 (1972).
40. Orme-Johnson, N. R., Hansen, R. E. & Beinert, H. *J. biol. Chem.* **249**, 1928–1939 (1974).
41. Fields, G. B. & Noble, R. L. *Int. J. Peptide Protein Res.* **33**, 1–53 (1989).
42. Bax, A. & Davis, D. G. *J. magn. Reson.* **65**, 355–360 (1985).
43. Marion, D. & Wuthrich, K. *Biochem. biophys. Res. Commun.* **113**, 967–974 (1983).
44. O'Shea, E. K., Rutkowski, R., Stafford, W. F. & Kim, P. S. *Science* **245**, 646–648 (1989).
45. Choma, C. T. et al. *J. Am. Chem. Soc.* **116**, 856–865 (1994).
46. Moser, C. C. & Dutton, P. L. *Biochim. biophys. Acta* **1101**, 171–176 (1992).
47. Crofts, A., Hacker, B., Barquera, B., Yun, C.-H. & Gennis, R. *Biochim. biophys. Acta* **1101**, 162–165 (1992).
48. Willie, A., Stayton, P. S., Sligar, S. G., Durham, B. & Millett, F. *Biochemistry* **31**, 7237–7242 (1992).
49. Wuttke, D. S., Bjerrum, M. J., Winkler, J. R. & Gray, H. B. *Science* **256**, 1007–1009 (1992).

ACKNOWLEDGEMENTS. Funded by grants from the US PHS (P.L.D. and A.J.W.).

LETTERS TO NATURE

Discovery of an X-ray source coincident with the soft γ -ray repeater 0525 – 66

R. E. Rothschild*, S. R. Kulkarni†
& R. E. Lingenfelter*

* Center for Astrophysics and Space Sciences 0111,
University of California, San Diego, La Jolla,
California 92093-0111, USA

† Division of Physics, Mathematics and Astronomy 105-24, California
Institute of Technology, Pasadena, California 91125, USA

ALTHOUGH γ -ray bursters (GRBs) have been known for more than 20 years, no source has ever been identified in its quiescent state, which might provide clues to its nature. On the other hand, two of the three known soft γ -ray repeaters (SGRs), which emit intermittent bursts of soft γ -rays, seem to be associated with supernova remnants^{1,2}, and the recent identification of X-rays from one of these, SGR1806 – 20, supports the suggestion that a pulsar inside the remnant is the source of the γ -rays^{3–5}. Here we report X-ray observations of SGR0525 – 66, which has been associated previously with the supernova remnant N49 (ref. 1). We identify point-like emission from a source coincident with SGR0525 – 66, which suggests that it too is a pulsar. The pulsar seems to be only about 5,000 years old and has a high transverse velocity of about 1,200 km s⁻¹, and we predict that the plerion (the region of radio synchrotron emission surrounding the pulsar) will be between 0.1 and 0.3 arcsec across. A high birth velocity has been estimated for the pulsar associated with SGR1806 – 20 also⁴, and this characteristic may be related to the reason why only a very few pulsars become SGRs.

The smallest γ -ray-burst error box is that for the 5 March 1979 event from the repeating burst source SGR0525 – 66 (ref. 6). Until recently this 0.09 arcmin² region was unique in that it overlapped the 2 arcmin² supernova remnant N49 in the Large Magellanic Cloud¹. Murakami *et al.* report³ that SGR1806 – 20 is also coincident with a supernova remnant, G10.0 – 0.3. Previous observations of N49 have reported a region of excess emis-

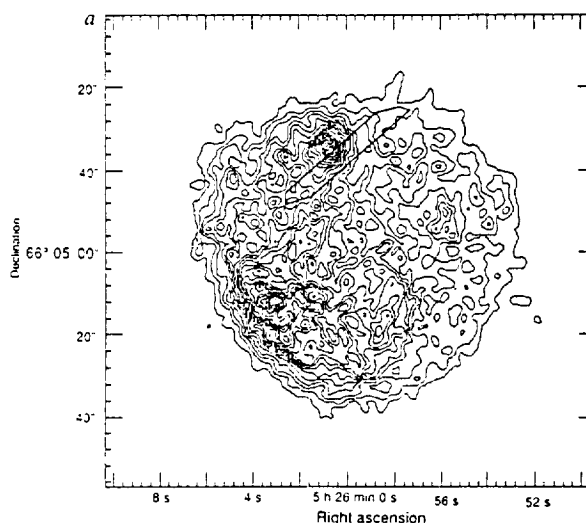


FIG. 1 a, Rosat High Resolution Imager smoothed contour plot of the supernova remnant N49 in the Large Magellanic Cloud. The point source at RA (J2000) 5 h 26 min 0.7 s and dec (J2000) – 66° 04' 35" is coincident with the error box (six-sided polygon) for SGR0525 – 66 which is the site of the 5 March 1979 γ -ray burst. Twenty, equally

spaced, contour intervals are displayed, ranging from 0.72 to 14.60 smoothed counts arcsec⁻¹. b, False-colour image of N49 from which the contours of a are derived. This represents ~20,000 s of livetime to the source.

sion, possibly point-like, within the nebula and consistent with the γ -ray-burst error box⁷. The satellite observations from Rosat of N49 over 3.5 days (beginning 17 March 1992) with the High Resolution Imager (HRI) yielded just over 20,000 s of livetime on the source. The resultant image contains $1.67 \pm 0.014 \times 10^4$ net counts in the 0.1–2.4 keV band for an average counting rate from N49 of $8.04 \pm 0.07 \times 10^{-1}$ counts s^{-1} . The image was smoothed using the PROS/IRAF software package, resulting in the contours and false-colour image shown in Fig. 1a and b respectively. A point-like source of excess emission is clearly seen in the northern portion of the remnant, as well as a broad, structured feature to the southeast. This morphology is consistent with that seen by HRI on the Einstein satellite 13 yr earlier⁸. The Interplanetary Network γ -ray error box for the intense 5 March 1979 γ -ray burst⁶, shown in Fig. 1a (six-sided polygon), is consistent with the northern hotspot in N49. The emission from this hotspot is centred at right ascension (RA) (J2000) 5 h 26 min 0.7 s and declination (dec.) (J2000) $-66^\circ 04' 35''$ with an uncertainty of $\sim 10''$ in radius. The excess counting rate from the hotspot is $1.51 \pm 0.13 \times 10^{-2}$ counts s^{-1} above that from an annulus of 5" inner radius and 10" outer radius centred on it. This represents $\sim 2\%$ of the remnant's 0.1–2.4 keV emission.

A radial profile centred on the hotspot was generated out to 10" with background selected from the next 5" in the radial direction. The resulting profile is shown in Fig. 2, along with a fit to a point-like radial gaussian response function plus a constant term representing any unsubtracted nebular emission. The fitted width of the response, $\sigma = 3.19'' \pm 1.57''$ is consistent with the combined point spread function of the Rosat telescope and the HRI of 2.12", and, thus, the spatial distribution of counts in the hotspot is indeed consistent with a point source of emission.

A spectral form is necessary to estimate the flux from the point source. Because no spectral information is available from the Rosat HRI, we assume a neutral hydrogen column density of 5×10^{20} atoms cm^{-2} along the line of sight⁹, and we estimate¹⁰ the energy-to-counts conversion factor (ECF) to be 7.5×10^{-2} counts $s^{-1}/(10^{-11}$ erg cm^{-2} s^{-1}) based upon a Crab-like pulsar with energy index of 1, and to be 6×10^{-2} counts $s^{-1}/(10^{-11}$ erg cm^{-2} s^{-1}) for a black body with a temperature of $\sim 2 \times 10^6$ K appropriate for a 5×10^3 -yr-old neutron star¹¹. The Crab ECF results in a flux estimate of $\sim 2.0 \times 10^{-12}$ ergs cm^{-2} s^{-1} , whereas that for the black body is $\sim 2.5 \times 10^{-12}$ ergs cm^{-2} s^{-1} . At the distance of the Large Magellanic Cloud (55 kpc)¹², the luminosity is $\sim 7 \times 10^{35}$ erg s^{-1} for the power law and $\sim 9 \times 10^{35}$ erg s^{-1} for the black body.

We have looked carefully at the optical emission in the vicinity of the point source, and although there is [O II], H α , and 6,100-Å continuum emission in this region, the emission is faint and diffuse with no bright object coincident with the X-ray hotspot. A comparison with [Fe XIV] 5,303-Å observations¹³ yields a similar conclusion. The brightest X-ray emission regions to the southeast, on the other hand, correlate quite well with the brightest [Fe XIV] regions. The absence of such a strong correlation near the point source is, perhaps, the best observational evidence for a non-nebular origin for the majority of the point source X-ray flux. Using star 3 of a previous optical investigation of the SGR0525–66 error box¹⁴ for comparison, we estimate an upper limit to the brightness of an optical point source to be $m_V \sim 20$ mag.

If we assume that the point-like source coincident with the N49 nebula is indeed a neutron star born in the supernova event, as also appears to be the case in SGR1806–20, its $\sim 25''$ offset from the centre of the remnant implies a transverse velocity of $v_p \sim 1,200$ km s^{-1} , given the age $t = 5.4 \times 10^3$ year (ref. 15). Only 3% of the pulsar population have velocities exceeding 500 km s^{-1} , and the highest measured¹⁶ velocity is 10³ km s^{-1} .

Calculations for the cooling of neutron stars¹¹ predict that after 5×10^3 yr the temperature will be $1\text{--}3 \times 10^6$ K and the bolometric luminosity will be in the range $2\text{--}50 \times 10^{33}$ erg s^{-1} . The present observations imply an X-ray luminosity (0.1–2.4 keV)

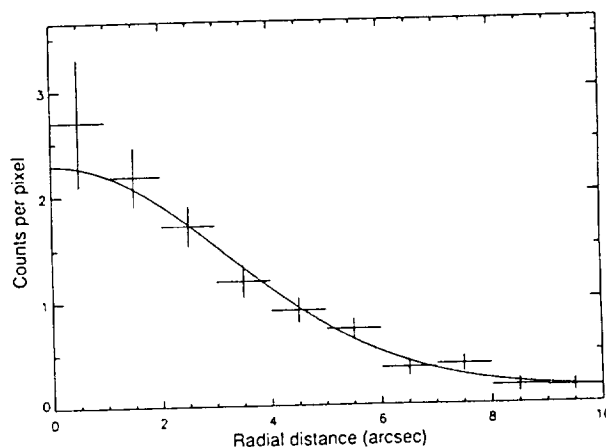


FIG. 2 Radial profile (data points) of the background-subtracted hotspot emission in N49 coincident with the γ -ray-burst error box. The background used was taken immediately surrounding the hotspot. The best-fit value of the width of the radial gaussian $\sigma = 3.19'' \pm 1.57''$ ($\chi^2_\nu = 0.71$ for $\nu = 7$ degrees of freedom) is consistent with the point source response value of 2.12". This best fit to the profile is given as the solid line.

of the order of 10^{36} erg s^{-1} . As the 0.1–2.4 keV flux for this temperature black body represents essentially the whole bolometric luminosity, a source of heating, such as γ -ray bursts or subsequent accretion, is required to account for the higher luminosity for the case of a black-body spectrum.

The existence of a non-thermal nebula, G10.0–0.3, around SGR1806–20 (ref. 4) indicates that soft γ -ray repeaters are also sources of high-energy particles and magnetic fields. Unlike most supernova remnants, G10.0–0.3 is centre filled and not a shell. The surface brightness increases towards the centre where quiescent X-ray emission has been detected by the ASCA satellite⁵. Two classes of neutron star systems have similar unusual radio nebulae: radio pulsars, such as the Crab nebula, and a rare type of luminous accreting X-ray binaries, (such as SS433 embedded in the nebula W50, and Cir X–1 (ref. 17)).

Our observations of SGR0525–66 can be interpreted in the context of these two possibilities for SGR1806–20. The persistent X-ray luminosity of the two are comparable. Because the line-of-sight extinction to the Large Magellanic Cloud is very low, unlike that to SGR1806–20, constraints on the model can be particularly strong. The absence of a bright optical star, as well as the persistent flux observed from SGR0525–66 being several orders of magnitude smaller than that of SS433 or Cir X–1, does not favour the model of an X-ray binary within a nebula. In the pulsar model, the X-ray point source can be interpreted as a compact synchrotron nebula, or a so-called plerion. A number of such supernova remnants with a plerion embedded within the shell exist in our Galaxy¹⁸. Assuming, as in other plerions, an efficiency $\eta \approx 10^{-2} \eta_{-2}$, where η_{-2} is the efficiency in units of 10^{-2} , for the conversion of spin-down luminosity (\dot{E}) into X-rays, we can infer $\dot{E} \propto B_{12}^2/P^4 \approx 7 \times 10^{37}$ erg s^{-1} , where B_{12} is the surface dipole field strength in units of 10^{12} G and P is the rotational period in seconds. Here we assume the simple magnetic dipole spin-down model for pulsars and $\eta_{-2} \approx 1\text{--}3$ for the known plerions¹⁹. The same model yields $P^2/B_{12}^2 = (t/17 \times 10^6 \text{ yr})$. From these two relations and our assumed \dot{E} and t , we find $B_{12} = 3\eta_{-2}^{1/2}$ and $P = 45\eta_{-2}^{1/2}$ ms.

An 8.0-s periodicity was found²⁰ in the emission after the peak in the 5 March 1979 burst, and a 23-ms quasi-periodic oscillation was reported²¹ during the peak of that burst. An 8.0-s rotation period would require an efficiency $\eta_{-2} \gg 1$; however, the 23-ms period, if confirmed, would be quite consistent with the proposed model, giving $\eta_{-2} = 0.26$ and $B_{12} = 1.5$.

Our hypothesis is testable. The radius of the plerion (r) is determined by the balance between the ambient pressure and the momentum flux of the pulsar's relativistic wind, $\dot{E}/4\pi r^2 c$, where c is the velocity of light. The ambient pressure is taken to be the larger of the two possibilities: the mean pressure in the supernova remnant ($p \approx n_0 m_H v_{sh}^2$), or the ram pressure due to the motion of the pulsar close to the edge of the supernova remnant ($p \sim 4n_0 m_H v_p^2$). Here $v_{sh} = 700 \text{ km s}^{-1}$ is the blast wave speed, $n_0 = 1 \text{ atom cm}^{-3}$, the density of the medium into which the supernova remnant is expanding¹⁵ and m_H is the mass of a hydrogen atom. We predict the plerion to have a size between 0.1 arcsec (if ram pressure dominates) and 0.3 arcsec (if the mean pressure in the supernova remnant dominates). In the former (likely) case, the plerion should be distinctly cometary whereas for the latter a spherical plerion is expected. It appears to us that sensitive high-resolution radio imaging of this region

would be a very worthwhile undertaking. Similarly, radio and X-ray spectra of the source would be valuable, as the characteristic power-law signature should be present at some level.

Although the high transverse velocity for this pulsar is near the extreme of observed values, the magnetic field and spin period parameters are not very different from those deduced for the pulsar population as a whole, and we have not had to invoke high field strengths²². If, indeed, SGR0525-66 is a typical young pulsar, then what property makes it special to undergo and repeat soft γ -ray bursting? The spatial offset of both SGR0525-66 and SGR1806-20 from the centres of their respective supernova remnants has been noted⁴ and this may imply an unusual manner for their birth. The precise connection between soft γ -ray repeating and offsets (high velocities?) remains to be identified. \square

Received 10 November 1993; accepted 10 February 1994.

1. Helfand, D. J. & Long, K. S. *Nature* **282**, 589-591 (1979).
2. Kulkarni, S. R. & Frail, D. A. *Nature* **365**, 33-35 (1993).
3. Cooke, B. A. *Nature* **366**, 413-414 (1993).
4. Kulkarni, S. R., Frail, D. A., Kassim, N. E., Murakami, T. & Vasisht, G. *Nature* **368**, 129-131 (1994).
5. Murakami, T. et al. *Nature* **368**, 127-129 (1994).
6. Cline, T. L. et al. *Astrophys. J.* **255**, L45-L48 (1982).
7. Rothschild, R. E., Lingenfelter, R. G., Seward, F. D. & Vancura, O. in *Compton Gamma-Ray Observatory AIP Conf. Proc.* Vol. 280 (eds Friedlander, M., Gehearts, N. & Macomb, D.) 808-812 (Am. Inst. Phys. Press, New York, 1993).
8. Mathewson, D. S. et al. *Astrophys. J. Suppl. Ser.* **51**, 345-355 (1983).
9. Pizzichini, G. et al. *Astrophys. J.* **301**, 641-649 (1986).
10. ROSAT Mission Description, Appendix F, Report No. NRA 91-OSSA-3 (Max-Planck-Institut Phys. Astrophys., Garching, 1991).
11. Nomoto, K. & Tsuruta, S. *Astrophys. J.* **250**, L19-L23 (1981).
12. Capaccioli, M., Della Valle, M., D'Onofrio, M. & Rosino, L. *Astrophys. J.* **360**, 63-67 (1990).

13. Dopita, M. A. & Mathewson, D. S. *Astrophys. J.* **231**, L147-L150 (1979).
14. Fishman, G. J., Duthie, J. G. & Dufour, R. J. *Astrophys. Space Sci.* **75**, 135-143 (1981).
15. Vancura, O., Blair, W. P., Long, K. S. & Raymond, J. C. *Astrophys. J.* **394**, 158-173 (1992).
16. Harrison, P. A., Lyne, A. G. & Anderson, B. *Mon. Not. R. astr. Soc.* **261**, 113-124 (1993).
17. Stewart, R. T., Caswell, J. L., Haynes, R. F. & Nelson, G. J. *Mon. Not. R. astr. Soc.* **261**, 593-598 (1993).
18. Weiler, K. W. & Sramek, R. A. *Rev. Astr. Astrophys.* **26**, 295-341 (1988).
19. Seward, F. D. & Wang, Z.-R. *Astrophys. J.* **332**, 199-205 (1988).
20. Mazets, E. P. et al. *Nature* **282**, 587-589 (1979).
21. Barat, C. et al. *Astr. Astrophys.* **126**, 400-402 (1983).
22. Duncan, R. C. & Thompson, C. *Astrophys. J.* **392**, L9-L13 (1992).

ACKNOWLEDGEMENTS. We thank R. Petre, M. Corcoran, and the Rosat Data Center duty scientists for assisting with the understanding of the data and its analysis, and O. Vancura for providing the optical images of N49. R.E.R. and R.E.L. are supported by NASA. S.R.K. is supported by US NSF, NASA and the Packard foundation.

ORIGINAL PAGE IS
OF POOR QUALITY